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CHANDRA DETECTIONS OF SCUBA GALAXIES AROUND HIGH-*Z* RADIO SOURCES

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ABSTRACT

The most massive galaxies in the present day universe are the giant ellipticals found in the centers of rich clusters. These have old, coeval stellar populations, suggesting they formed at high redshift, and are expected to host supermassive black holes (SMBHs). The recent detection of several high-redshift radio galaxies (HzRGs) at submillimeter (submm) wavelengths confirms that indeed some massive galaxies may have formed the bulk of their stellar populations in spectacular dust-enshrouded starbursts at high redshift. In this letter we compare sensitive *Chandra* X-ray images – which identify actively-fueled SMBHs – and submm observations – capable of detecting obscured activity in luminous galaxies at high redshift – of the environments of three HzRGs. These observations exhibit overdensities of X-ray sources in all three fields and a close correspondence between the *Chandra* and SCUBA populations. This suggests that both substantial star formation and nuclear activity may be occuring in these regions. We identify possible pairs of *Chandra* sources with each of two SCUBA sources, suggesting that their ultraluminous activity may be triggered by the interaction of two *massive* galaxies, each of which hosts an accreting SMBH. The presence of two SMBHs in the resulting remanent is predicted to produce a flattened stellar core in the galaxy, a morphological signature frequently seen in luminous cluster ellipticals. Hence the confirmation of pairs of *Chandra* sources within individual, luminous SCUBA galaxies would provide additional evidence that these galaxies at $z \sim 2$–4 are the progenitors of the giant elliptical galaxies found in clusters at the present-day.

Subject headings: cosmology: observations — galaxies: individual (SMM J06509+4130, SMM J06509+4131, SMM J11409–2629, SMM J17142+5016) — galaxies: evolution — galaxies: formation

1. INTRODUCTION

Studies of luminous ellipticals in high-density regions out to $z \sim 1$ suggest that their stellar populations are formed via a short burst of star formation at high-z (probably $z > 2$), with little additional star formation at $z < 1$ (Bower, Lucey & Ellis 1992; Ellis et al. 1997; Stanford et al. 1998; Poggianti et al. 2001; Kelson et al. 2001). Further support for this conclusion comes from the apparent lack of evolution in the metallicity of the intracluster medium out to $z \sim 1$ (Tozzi et al. 2003). The short dynamical times expected in the densest regions at high-z coupled with the intense star formation necessary to form the stellar population of a luminous elliptical suggest that this formation phase may resemble a classical "monolithic" collapse – even within a hierarchical cosmogony (Kauffmann 1996; Baugh et al. 1998). A clear test of this paradigm is to *directly* observe the epoch of elliptical formation in high-z protoclusters. There are expected to be two distinct observational signatures of this formation phase.

Firstly, the intensity of the star formation event and the high metallicity of the stars in ellipticals today (as well as the intracluster medium) all argue that this activity will produce a large amount of dust. This will obscure the later phases of the starburst and the most active systems, those with star formation rates of $> 10^2$–$10^3 M_\odot$ yr^{-1}, would be classed as ultraluminous infrared galaxies (ULIRGs) with far-infrared luminosities of $> 10^{12} L_\odot$. The sensitivity of submillimeter (submm) cameras such as SCUBA on the JCMT is sufficient to detect these systems out to $z \gg 1$ (Chapman et al. 2003).

The second observational signature derives from the apparently close correlation seen locally between the mass of central black holes and the mass of the spheroid which hosts them (Kormendy & Richstone 1995; Magorrian et al. 1998; Gebhardt et al. 2000; Ferrarese & Merritt 2000), which in turn suggests a tight linkage between the formation of these components. As the most massive spheroids, luminous cluster ellipticals are expected to host supermassive black holes (SMBH), $> 10^9$M$_\odot$. Thus many young ellipticals may also exhibit signatures of nuclear activity as their SMBH will be actively fueled and growing during the dusty starburst phase, and should be detectable in deep X-ray imaging.

To investigate the formation of the elliptical galaxy population of rich clusters using these observational tools we need to identify the likely site of their formation: proto-clusters at $z > 2$. In standard cosmological models, massive galaxies at $z > 2$ are expected to strongly cluster in the deepest potential wells, onto which other galaxies later accrete, assembling the rich clusters we see at $z \sim 0$. The strongly clustered population of luminous high-z radio galaxies (HzRG) are believed to host massive black holes and thus may represent some of the most massive galaxies at these epochs (e.g. de Breuck et al. 2000) which in turn could trace some of the highest density environments. The association of luminous radio galaxies with overdense structures at high-z is supported by the identification of modest excesses of companion galaxies around HzRGs in the optical/near-infrared (e.g. Röttgering et al. 1996), X-ray (Pentericci et al. 2002, P02; Fig. 1) and submm wavebands (Ivison et al. 2000, I00; Stevens et al. 2003; Fig. 1).

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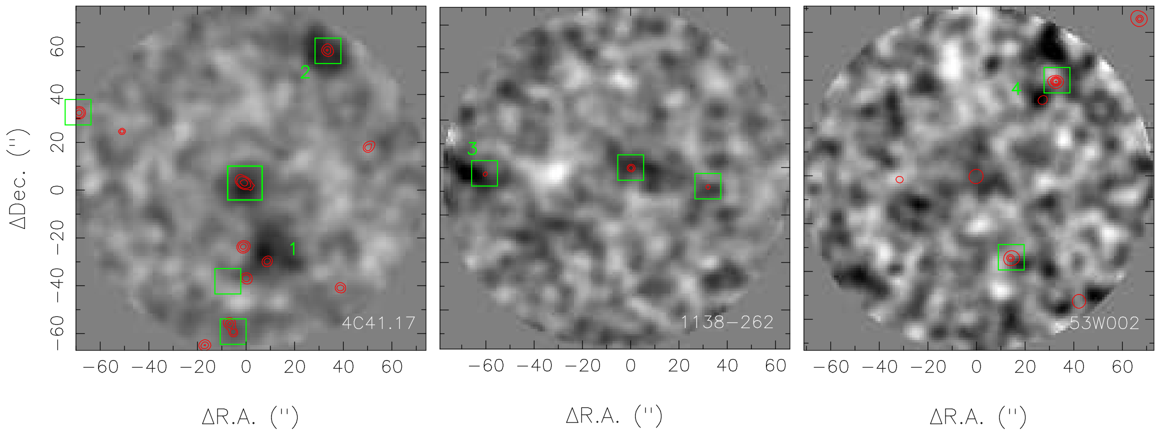

FIG. 1.— The 0.5–2 keV *Chandra* X-ray images of the regions around 4C 41.17 (Scharf et al. 2003), MRC1138–262 (P02) and 53W002 (White et al. 2003), each overlayed as a contour map on a grayscale representation of the relevant 850μm SCUBA map from Stevens et al. (2003). We mark with □ the positions of the hard-band sources detected in these fields. Notice the X-ray counterparts to four of the SCUBA sources in these field (numbered as in Table 1), as well as the X-ray emission from the radio galaxies at the center of each field.

We have brought together these two observational tools: submm and X-ray imaging, to search for the formation phase of luminous elliptical galaxies in putative high density environments around HzRGs. We have identified X-ray counterparts to the SCUBA sources in the fields of three HzRGs. We discuss the properties of these sources and the information they provide on the formation of SMBHs and the early stages of the growth of massive cluster elliptical galaxies. We assume a cosmology with $\Omega_m = 0.27$, $\Omega_\Lambda = 0.73$ and $H_o = 71\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$.

2. ANALYSIS AND RESULTS

A search of the *Chandra* archive shows that three fields from the SCUBA survey of HzRG by Stevens et al. (2003) have moderate or deep X-ray imaging observations. These are 4C 41.17 ($z = 3.79$), MRC 1138–262 ($z = 2.16$) and 53W002 ($z = 2.39$), with useable integration times of 135.1 ks, 32.5 ks and 32.8 ks respectively. The *Chandra* observations of 4C 41.17 are discussed in Scharf et al. (2003), while those for MRC 1138–262 are detailed in P02 and Carilli et al. (2002), and 53W002 is presented in White et al. (2003). We refer the reader to these papers for more details of the observations and their reduction. Sources have been detected and measured in these images using the CIAO software WAVDETECT algorithm with default settings. Hardness ratios (HR) are determined as $(H-S)/(H+S)$ for a 0.5–2 keV soft band (S), and 2–10 keV hard band (H). To convert count rates to fluxes we assume a Galactic $\log N(\mathrm{H\,I}) = 21.0$ for all sources and a power law spectrum with photon index $\Gamma = 1.5$ and intrinsic $\log N(\mathrm{H\,I}) = 23.0$ for HR> -0.5 and $\Gamma = 2.2$ with no intrinsic absorption for HR< -0.5 (c.f. Tozzi et al. 2001). Luminosities are calculated in the 0.3–10 keV rest frame using XSPEC, errors assume Poissonian count rate uncertainties.

In all three fields excesses of soft-band sources are seen: P02 show that the MRC 1138–262 field has a modest excess of soft-band sources amounting to a factor of 50% (in an $8' \times 8'$ field), while White et al. (2003) estimate an overdensity of 2–3× in soft-band sources around 53W002. In the 4C 41.17 field we find 11 soft-band sources brighter than $S_{0.5-2} = 0.2 \times 10^{-15}\,\mathrm{erg\,s^{-1}\,cm^{-2}}$ within the SCUBA field (Fig. 1, 2.1′, 1 Mpc diameter), compared to a blank field expectation of ~ 2 (Rosati et al. 2002). Thus we have a factor of 5–6× overdensity of soft-band sources in the vicinity of 4C 41.17 (there is also a 2× overdensity of hard-band sources in this field).

As described by P02, the X-ray sources in MRC 1138–262 also display a strongly filamentary pattern around the radio galaxy suggestive of associated large scale structure. A similar, but weaker filamentary structure may extend to the south of 4C 41.17 (Fig. 1). The existance of overdense structures around the HzRGs is supported by follow-up of the X-ray sources in the MRC 1138–262 field where at least 2, and possibly up to 5, sources lie at the same redshift as the HzRG (P02). Similarly, for 53W002, White et al. (2003) identify at least 3 X-ray bright AGN at the same redshift as the HzRG. On-going spectroscopy of the 4C 41.17 field has so far confirmed one *Chandra* companion at $z = 3.8$.

Submm maps with noise levels of $\sim$ 1.0–1.5 mJy are available of these three fields from the 850μm SCUBA survey of Stevens et al. (2003), with the first results on 4C 41.17 reported in I00. These cleaned maps also show modest overdensities of submm sources compared to blank fields, with at least one example, SMM J17142+5016 in the 53W002 field, spectroscopically confirmed at the same redshift as the radio galaxy (Smail et al. 2003a, S03a). There are 3 $>$ 4-σ submm sources around 4C 41.17 (I00), 3 around MRC 1137–262 (Stevens et al. 2003) and 4 around 53W002 (S03a). Using the flux limits for the three fields and the compilation of SCUBA counts in Smail et al. (2002), we estimate that the HzRG fields show 2× overdensities of SCUBA galaxies compared to the field, with roughly 4–5 of the sources likely to be unrelated field galaxies.

To compare the X-ray and submm emission in these fields we align the two maps. The astrometric precision of the 850μm maps is $\pm 3''$ rms and small shifts of less than this magnitude have been applied to align the submm emission with the radio centroids for the luminous HzRGs in these fields. The X-ray images are similarly tied to the radio frame with an absolute precision of $0.5''$ rms using the positions of several X-ray and radio bright AGN in each field.

Due to the extended nature of the submm emission in many of the SCUBA sources in our fields (I00; Stevens et al. 2003) we choose to test the association of *Chandra* sources with the SCUBA galaxies by searching for statistical excesses of submm emission around the precisely-located X-ray source. To calculate these fluxes we use a $3''$-radius aperture which represents the relative uncertainty of the astrometry between the *Chandra*

CATALOG OF SCUBA/*Chandra* SOURCES

Source	R.A. (J2000)	Dec. (J2000)	S_{850} (mJy)	$S_{0.5-2}$ (10^{-15} erg s^{-1} cm^{-2})	S_{2-10}	HR	$L_X(0.3-10)$ (10^{43} erg s^{-1})	α_{SX}^{a}	P^{b}	Comment
1) **SMM J06509+4130**	06 50 51.2	+41 30 05	15.6±1.8	...	...	...	...	1.18	...	4C 41.17 HzRG850.1, I00
CXJ 065051.3+412958	06 50 51.30	+41 29 58.1	...	0.26±0.09	0.93±0.40	−0.3	3.2±1.0	1.28	0.004	HzRG850.1/K3, I00
CXJ 065052.1+412951	06 50 52.09	+41 29 51.2	...	0.38±1.0	1.9±0.6	−0.1	5.6±1.2	1.24	0.047	
CXJ 065052.2+413004	06 50 52.19	+41 30 04.5	...	0.85±1.6	0.44±0.25	−0.8	13.0±2.0	1.25	0.221	LR1, Lacy & Rawlings (1996)
2) **SMM J06509+4131**	06 50 49.3	+41 31 27	8.7±1.2	...	...	...	...	1.18	...	4C 41.17 HzRG850.2, I00
CXJ 065049.1+413127	06 50 49.13	+41 31 26.5	...	0.43±0.11	3.3±0.8	+0.1	8.0±1.2	1.18	0.016	HzRG850.2/K1, I00
3) **SMM J11409–2629**	11 40 53.3	−26 29 11	7.4±1.5	...	...	...	...	1.07	...	MRC 1138–262, Stevens et al. (2003)
CXJ 1114052.8–262911	11 40 52.84	−26 29 11.2	...	5.1±0.7	5.2±1.7	−0.7	4.2±0.4	1.07	0.009	#9 ($z\sim 2.16$), P02
4) **SMM J17142+5016**	17 14 12.1	+50 16 02	5.6±0.9	...	...	...	...	1.14	...	53W002 #18 (z = 2.39), S03a
CXJ 171412.0+501602	17 14 11.97	+50 16 02.3	...	0.48±0.24	3.1±1.6	0.0	4.6±1.5	1.14	0.002	

a) The submm–X-ray spectral index (Fabian et al. 2000). The values for the SCUBA galaxies assume all the X-ray sources contribute to the submm emission, while those quoted for the individual *Chandra* sources assume all the submm emission arises just from that source.
b) Likelihood of detecting the observed submm flux at the X-ray position by random chance.

and SCUBA maps. We measure the flux in $\sim 10^3$ randomly-placed apertures across the SCUBA map and calculate the fraction of these which exceed that measured at the positions of the *Chandra* sources. This procedure provides a likelihood for each association and allows us to identify statistically significant (>98% c.l.) associations between X-ray sources and 4 out of the 10 SCUBA galaxies in these fields (we ignore the central HzRG in each field each of which are detected in both the X-ray and submm wavebands, Fig. 1). It should be noted that these associations may result either from a direct correspondence between the sources in the two wavebands, or because both classes populate the same structures around the HzRGs. We list in Table 1 the details of these associations and briefly discuss the individual cases below.

1) SMM J06509+4130 – this is the very bright ($L_{bol} \sim 10^{13} L_{\odot}$), southern SCUBA source in Fig. 1a (HzRG850.1 from I00). This resolved submm source (70 kpc diameter) coincides with the soft-band *Chandra* source CXJ 065051.3+412958, which is identified as the K = 19.4 very red object HzRG850.1/K3 from I00. A second soft-band *Chandra* source to the South-East, CXJ 065052.1+412951, is also associated with the submm emission (<5% chance of this being random coincidence). This source has no obvious optical or near-IR counterparts in the imaging discussed by I00 indicating $K > 20.0$ and $R > 26.0$. A third, bright soft-band *Chandra* source lies just outside the region of submm emission to the East (Fig. 1a). This source is coincident with a red stellar object (LR1 from Lacy & Rawlings 1996) with *UVR* colors consistent with either a foreground star or a $z \sim 3.8$ AGN (there is a 6% chance of an unrelated X-ray source falling this close to the SCUBA position). Finally, a hard-band source with a faint K-band counterpart is detected 18″ to the South-East, although this is unlikely to be directly related to the SCUBA galaxy.

2) SMM J06509+4131 – this is the second, bright and spatially-extended, SCUBA galaxy (HzRG850.2 in I00) in the 4C 41.17 field (Fig. 1a) and is associated with the *Chandra* source CXJ 065049.1+413127. The X-ray source is detected in both the hard and soft-bands and is coincident with the K1 counterpart of HzRG850.2 from I00. K1 is one of a pair of faint, very red galaxies separated by $\sim 2''$.

3) SMM J11409–2629 – this is the brightest submm source in the vicinity of the z = 2.16 radio galaxy MRC1138–262 mapped by Stevens et al. (2003; Fig. 1b). The *Chandra* source CXJ 1114052.8–262911 (#9 from P02) is statistically associated with the SCUBA source (Table 1). P02 report that #9 exhibits an Lyα emission-line excess, indicating that it probably lies at $z \sim 2.16$, which would place this SCUBA galaxy in the striking filament seen across this field.

4) SMM J17142+5016 – this relatively faint SCUBA galaxy has been identified by S03a with a weak AGN, #18 from the catalog of Keel et al. (2002). The *Chandra* source coincides exactly with the optical/near-IR counterpart and hence we can unequivocally associate both the X-ray and luminous submm emission with this galaxy which is spectroscopically-confirmed as a companion to the radio galaxy at z = 2.39. A much brighter X-ray source is detected 9″ (75 kpc) to the North-West, coincident with the broad-line z = 2.39 AGN #19 (Keel et al. 2002), although this source is undetected in the SCUBA map (Fig. 1c). There is a 2% chance that this source would fall within 9″ of the SCUBA galaxy by random chance.

In summary, we detect X-ray counterparts to four luminous submm sources in the fields of three z = 2.2–3.8 HzRGs. Moreover, one of these X-ray sources has the same redshift as the radio galaxy in its vicinity and a second is also likely to be at the same redshift as its neighboring HzRG. These identifications confirm the presence of luminous dust-obscured galaxies containing actively-fueled SMBHs in the environments of radio galaxies at $z > 2$. We give their hardness ratios and submm/X-ray spectral indices (α_{SX}) in Table 1 and also estimate their X-ray luminosities assuming they lie at the same redshifts as the relevant HzRG. For all four sources these X-ray properties are consistent with obscured, Seyfert-like systems, $L_X \sim 10^{43}$–10^{44} ergs s^{-1} with absorbing columns of N(HI) $\gtrsim 10^{23}$ cm^{-2} (Alexander et al. 2003a; Fabian et al. 2000). We obtain a lower limit on the black hole masses in these systems of $\gtrsim 10^7$M$_{\odot}$ by assuming that they are accreting at their Eddington limit, or $\sim 10^8$M$_{\odot}$ if their SMBHs are accreting at a similar rate to local Seyferts.

3. DISCUSSION AND CONCLUSIONS

Our identifications of *Chandra* counterparts to the SCUBA galaxies in these fields are statistical in nature and hence the possibility exists that the two populations are simply tracing the same large-scale structures, rather than being *directly* related. However, the relatively small spatial scale of the associations, $\lesssim$ 100 kpc, suggests that there is a direct relationship and so the following discussion proceeds on that assumption.

The rate of detection of SCUBA sources in our *Chandra* maps is $\sim$ 40%, this is somewhat higher than the $\sim$ 5–10% detection rate reported from comparable-depth *Chandra* and *XMM-Newton* observations (Barger et al. 2001; Ivison et al. 2002; Almaini et al. 2003; Waskett et al. 2003) and is simi-

lar to that achieved in the far-deeper, 2-Ms *Chandra* integration discussed by Alexander et al. (2003), who detect four out of ten ≥ 5 mJy SCUBA sources above a flux limit of $S_{0.5\text{–}8} \geq 1 \times 10^{-15}$ erg s^{-1} cm^{-2}. Our high detection rate could either reflect enhanced X-ray emission from SCUBA galaxies in these environments, or may instead simply point to an increase in the detection rate of $\gtrsim 5$ mJy SCUBA sources just below the flux limits of the shallower surveys, e.g. $S_{0.5\text{–}8} \sim 3 \times 10^{-15}$ erg s^{-1} cm^{-2} for the Almaini et al. (2003) study (Manners et al. 2003).

We also identify a significant overdensity of *Chandra* sources within a 1-Mpc region around the radio source in the 4C 41.17 field, in both the soft and hard-bands. Similar overdensities have been previously reported around MRC 1138–262 (P02) and 53W002 (White et al. 2003), suggesting that the environment of HzRGs at $z > 2$ are also fertile ground for triggering AGN activity. This activity appears to be linked to the excess of luminous submm sources found in these regions, as can be seen if we measure the mean submm flux of *all Chandra* sources within our SCUBA maps. We estimate a mean flux of 2.6 ± 0.7 mJy from the 15 soft-band sources (excluding the 3 radio galaxies). This flux is roughly twice that of blank-field *Chandra* sources at similar X-ray flux limits (Almaini et al. 2003; Barger et al. 2001; Waskett et al. 2003), although the result is only significant at the ~ 2-σ level due to the small sample size.

Two of the SCUBA sources detected by *Chandra* are particularly noteworthy. The first is SMM J06509+4130 (HzRG850.1 from I00), a very luminous and spatially-extended submm source which is apparently associated with two X-ray sources (separated by $11''$ or 80 kpc if at $z = 3.8$), with two other X-ray sources in close proximity. A second X-ray detected SCUBA source is SMM J17142+5016, which also has an X-ray bright companion, 53W002#19, at a projected distance of 80 kpc and a velocity offset of only 400 km s^{-1} (Keel et al. 2002). Two similar pairs of *Chandra* sources associated with SCUBA galaxies, with separations of 2–3$''$, have been reported by Alexander et al. (2003a) from a sample of 10 SCUBA galaxies in the CDF-N. Thus from a combined sample of 21 SCUBA sources we have 3 (14%) with pairs of *Chandra* counterparts brighter than $S_{0.5\text{–}8} \sim 10^{-15}$ erg s^{-1} cm^{-2}, this is 7$\times$ higher than the occurence of similar separation pairs in the general *Chandra* population at this flux limit (9/460 or 2%, Alexander et al. 2003b).

These SCUBA galaxies with pairs of *Chandra* counterparts are remarkable systems – suggesting that the ultraluminous SCUBA events are triggered by the interaction between multiple(?) massive galaxies. The activity in these paired *Chandra* sources implies that they are currently interacting and their separations then suggests that the pericentric passage probably occured within the last ~ 100 Myrs, consistent with the expected life time of the starbursts in SCUBA galaxies (Smail et al. 2003b). Moreover, the presence of SMBHs in the progenitors means they have either been formed on the timescale of the current interaction, or these galaxies had sufficient prior activity to build a SMBH (and by implication a massive spheroid), yet still retain significant quantities of gas needed to power the current, obscured starburst.

The final merger of these pairs of galaxies, probably within the next 100–200 Myrs or by $z \sim 3.4$ for the 4C 41.17 pair, will produce a remanent which hosts two SMBHs. The interaction of the two SMBHs is predicted to produce a flattening of the stellar distribution in the core of the remanent (Ravindranath, Ho & Filippenko 2002). This is a structural feature common to bright elliptical galaxies, and also one which is preferentially found in ellipticals in clusters (Laine et al. 2003; Quillen, Bower & Stritzinger 2000). Hence the identification of multiple *Chandra* sources within a modest fraction of the SCUBA population is consistent with the expectation that these galaxies will evolve into luminous ellipticals at the present-day and that the environments we find them in at high-z are regions which will go on to become the cores of rich clusters. However, the relatively modest mass estimates we derive for these SMBH, $\gtrsim 10^7$–10^8M$_\odot$, compared to the $\sim 10^9$M$_\odot$ SMBHs found in bright ellipticals today gives scope for subsequent growth of the SMBHs in these systems during the final stages of the merger.

The success rate for identifying *Chandra* counterparts to SCUBA galaxies in our X-ray images suggests that X-ray observations may provide a useful route to localise the submm-emitting galaxies in these regions. This would normally be achieved through sensitive radio observations (e.g. Ivison et al. 2002), but the presence of the very bright radio source in these fields restricts the depth that can be achieved due to dynamic-range limitations.

We summarise the main results of this work. We study moderate depth X-ray observations of luminous submm galaxies in the fields of three luminous radio galaxies at $z = 2.2$–3.8. We identify a significant overdensity of X-ray sources around the most distant target, 4C 41.17 at $z = 3.8$. We also identify possible X-ray counterparts to 4 submm galaxies in these fields (as well as the 3 submm-luminous central radio galaxies). These associations either indicate a direct relationship between the *Chandra* and SCUBA sources, or simply that both populations are tracing the same large-scale structures. Spectroscopic and narrow-band imaging suggests that two of these *Chandra* sources lie at the same redshifts as their neighbouring HzRGs, hence our identification of these objects as submm sources extends the number of dusty, ultraluminous galaxies likely to reside in structures around radio galaxies at $z > 2$. We also highlight the properties of two of these submm galaxies, one appears to be associated with at least *two Chandra* sources, while the second has a *Chandra* counterpart and also a bright X-ray companion in close proximity. These results suggest that the ultraluminous activity in some fraction of the SCUBA population may result from the interaction of pairs of massive galaxies, each of which can be identified by the X-ray emission from their central supermassive black holes. The presence of two SMBHs in the resulting merger remanent is predicted to produce a clear structural signature, a flattened core, in the stellar profile. Such features are commonly observed in luminous elliptical galaxies in clusters, suggesting a link between SCUBA galaxies at $z > 2$–4 and the population of luminous elliptical galaxies seen in clusters today.

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